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Time course of early mesopic adaptation to luminance decrements and recovery of spatial resolution

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Abstract

The time course of recovery of spatial resolution following adaptation to a uniform field was measured for test probes presented at lower illuminance than the adapting field. Six observers were tested in a Maxwellian-view system using 20° adapting fields of 1.6–2.6 log photopic trolands. Test stimuli were 7°, 250 ms Gabor patches (1 and 6 cpd) of mean retinal illuminance 2–3 log units lower than the adapting field. During the 9 s after adapting field offset, contrast thresholds for orientation discrimination followed an exponential-decay function and showed longer recovery times for larger illuminance decrements and higher spatial frequency.

Keywords: Light adaptation; Dark adaptation; Mesopic sensitivity; Visual acuity; Contrast sensitivity; Night vision; Aging

1. Introduction

Recent studies of foveal light and dark adaptation have been designed to yield information on the neural processes underlying gain adjustment. Most of these studies have employed a 'probe-flash' paradigm, in which the probe (a test flash) is an increment on a test field of a luminance different from that of the adapting field which it replaces. Changes in increment threshold due to increase or decrease of background luminance can be used to determine the temporal and spatial dynamics of sensitivity regulation.

Several models (Geisler, 1983; Graham & Hood, 1992; Hayhoe, Levin, & Koshel, 1992; Wilson, 1997) have succeeded in accounting for increment threshold changes following an abrupt increase in background luminance (the 'background-onset effect'). It is less clear that they can account for changes that follow a *decrease* in background luminance. Graham and Hood (1992; von Wiegand, Hood, & Graham, 1995) note the bearing that their 'merged model' (combining increment threshold and spatial frequency approaches) may have on a 'background-offset effect,' but they do not attempt to apply it to the scanty data available in the literature. The main limitation of Geisler's model was its inability to predict increment thresholds during very early dark adaptation when the test field was lower than the adapting field (Geisler, 1983).

In addition to these theoretical considerations, we were led to look at probe-flash data in order to address an issue concerning the safety of pilots using night vision goggles (NVGs). During night operations a pilot wearing NVGs may become adapted to a high mesopic or low photopic luminance level (10 fL or higher) under ambient conditions which include sources of high intensity illumination such as flares. When looking under the goggles at cockpit instruments, the pilot may need to acquire information immediately at a luminance level as much as 3 log units lower (0.01–0.03 fL). Can the pilot expect to be able to read the instruments at once, or will there be a delay of some seconds while adapting to this lower luminance?

Bodmann, Kokoschka, and Greule (1987) traced letter discrimination thresholds for 60 s following replacement of an adapting field at 3.3 log cd/m^2 by a test field at 0.9 log cd/m^2, but these luminances are about 2 log units above the range pertinent for the NVG user. Studies of increment threshold (Geisler, 1983; Hayhoe,

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Benimoff, & Hood, 1987; Hayhoe et al., 1992) offer no definitive evidence about instrument reading tasks, even in the few conditions when their adapting field and test field luminances are in the relevant mesopic range. In two recent papers (Hahn & Geisler, 1995; Kortum & Geisler, 1995), Geisler and colleagues moved away from increment detection toward an acuity task. Kortum and Geisler obtained amplitude thresholds for *orientation discrimination* of 6.8° 'increment Gabor functions'[1] presented on test fields immediately following the offset of an adapting field with luminance as much as 3 or 4 log units higher or lower than that of the test field. Their data provide amplitude thresholds at the moment of offset for one adapting field (1.91 log td) within the range of interest. These thresholds were about a log unit higher than thresholds for the same test field when the eye was fully dark adapted, but Kortum and Geisler obtained no data on changes in sensitivity during the seconds following adapting field offset.

Accordingly, an experiment was undertaken to provide data on the time course of contrast thresholds for orientation discrimination of Gabor functions following an abrupt decrease in background luminance.

2. Method

The experiment employed two optical channels in Maxwellian view, one to present the adapting field and the other to present a uniform test field which could be modified by a Gabor function for 250 ms at delays varying from 0.25 to 9 s after test field replaced adapting field. Channel 1 used light from a xenon arc lamp, passed through a holographic grating monochromator, to produce a 20° adapting field (532 nm, 8 nm bandwidth at half power). Channel 2 used light from a Barco color monitor (CCID 7551), passed through an astronomical telescope optical system, to form a 7° test field at the retina. Only the green gun of the monitor was used; its dominant wavelength was also 532 nm. Retinal illuminance in the two channels was controlled by neutral density filters and/or a neutral density wedge.

For the test field, Gabor patches of obliquely oriented, static sinewave gratings were generated by the GSP board of a Cambridge Research VSG system. The VSG has built-in hardware for pseudo-12-bit resolution to permit fine luminance resolution when only a small luminance range is required. Eq. (1) describes the test stimulus luminance distribution,

$$f(x, y) = L_0\{1 + m \cdot \sin(by) \cdot e^{-[(x/s)^2 + (y/s)^2]}\} \quad (1)$$

where L_0 is mean luminance of the test field, m is amplitude, b is spatial frequency, and s is the space constant ($SD/\sqrt{2}$) of the Gaussian envelope along the major and minor axes of the resulting 2D-Gaussian envelope. The value of s was set at one-quarter of the 7° test field, 1.75°. The monitor was run at half the maximum luminance in order to maximize the available range of contrasts.

Luminance of Channel 1 was measured using a Minolta LS-100 photometer and converted to retinal illuminance by the method of Westheimer (1966). Channel 2 was equated to Channel 1 based on radiometric measurements (United Detector Technology, Model 181). The various physical measures were confirmed by homochromatic brightness matches between the adapting and test fields. Spectral characteristics of the monitor were measured with a Photo Research PR-703A/PC spectroradiometer. A Cambridge Research OptiCal system was used on a regular basis throughout the study for gamma correction of the monitor. The neutral density filters and wedge were calibrated separately for both channels using the UDT radiometer.

3. Procedure

Four observers participated in all conditions of this experiment; two were male (EB, age 22; RC, age 47) and two were female (KS, age 21; CS, age 51). Two additional observers (WS, age 22; MC, age 41) completed five test conditions. All were in good general health and had normal retinae based on direct ophthalmoscopy by an experienced optometrist. Best corrected distance visual acuities were $\geq 20/20$ as determined by the Bailey–Lovie Log MAR chart. All were normal trichromats according to the HRR plates, the FM-desaturated D-15, and the Neitz anomaloscope tests.

With head position stabilized by a bite bar, observers were carefully aligned so that light from each channel passed through the center of the pupil. After 10 min of dark adaptation, the adapting field was presented for 2 min; it was then replaced by the smaller test field. Both adapting field and test field were centered on the same fixation mark. Following a specified delay, a grating appeared for 250 ms. The grating could be oriented at 45 or 135°; the observer responded by pressing the right or left of two response keys. Then the adapting field replaced the test field for a further 15 s before the next trial. A pilot study confirmed that 15 s was an adequate

[1] An increment Gabor function, as defined by Hahn and Geisler (1995), is a Gabor function that modulates entirely above the background; it is the sum of a Gaussian pattern and a Gabor pattern of the same spatial width. The experiment reported here used Gabor functions that were increments and decrements around the mean test field luminance.

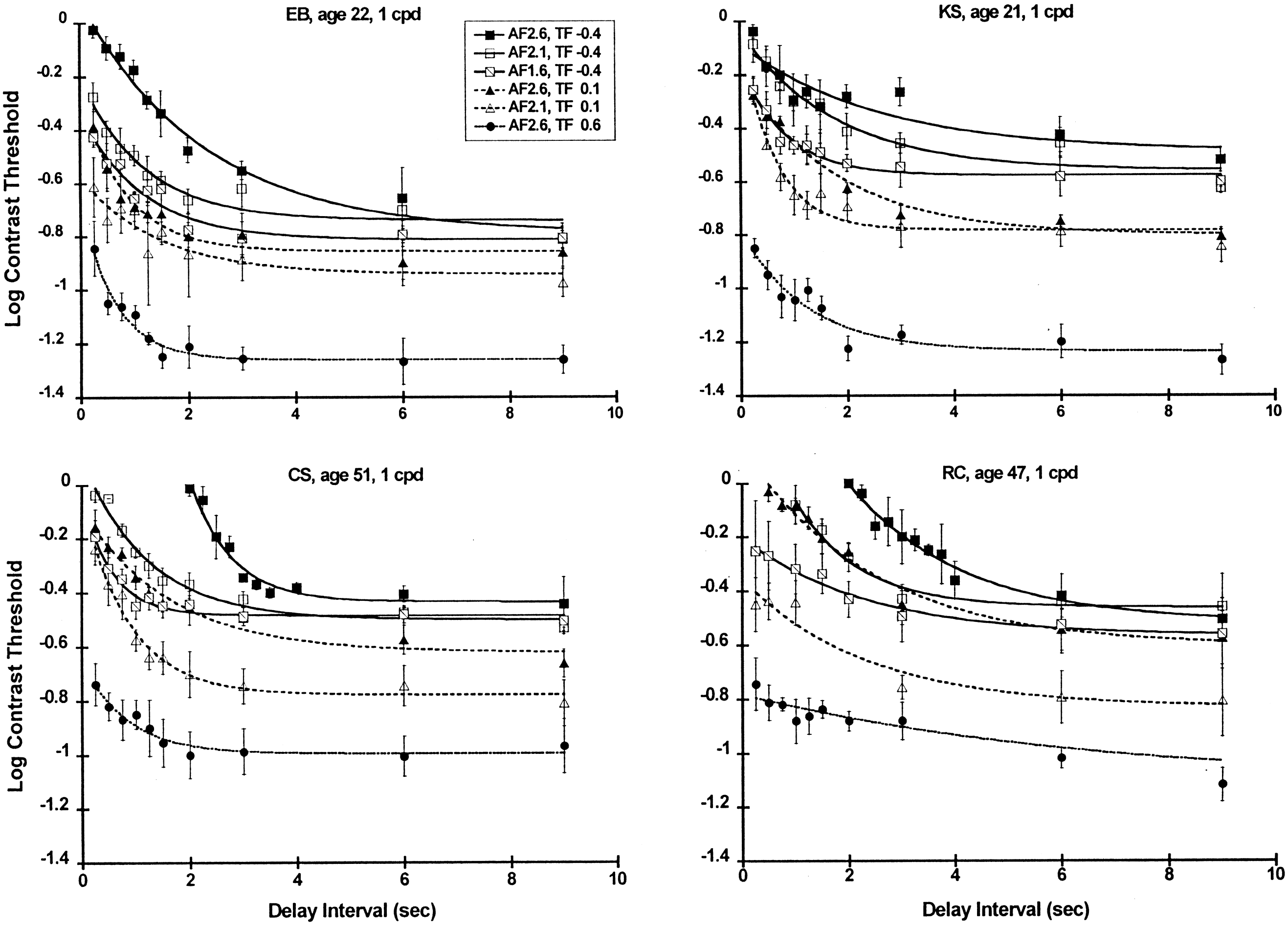

Fig. 1. Log contrast threshold plotted as a function of delay interval for 1 cpd gratings. Symbol key denotes adapting field (AF) and test field (TF) illuminances in log trolands.

duration to maintain complete adaptation to the adapting field.

Contrast thresholds for each delay interval were obtained by a three correct/one incorrect double staircase-reversal algorithm. Ascending and descending staircases were interleaved. Trials continued through three reversals, and threshold estimates were calculated from the mean of the last two reversals of each staircase. The contrast thresholds reported here are means of at least four threshold estimates, obtained in different experimental sessions.

Three adapting field levels spaced at 0.5 log td intervals were chosen to cover the appropriate range. Test field illuminances were chosen to be 2, 2.5, or 3 log td lower than the adapting field illuminances of 2.6, 2.1 and 1.6 log td. Since illuminances below -0.4 log td lie outside the range of interest for this problem, only six of the possible nine combinations of adapting (AF) and test field (TF) luminance were studied. These combinations are listed in the figure keys. All four observers completed the six conditions with gratings of 1 cpd. Each observer completed as many conditions as possible with 6 cpd gratings.

4. Results

Fig. 1 summarizes the contrast-threshold data collected with a 1 cpd grating. Individual data for the principal four observers are shown separately; each data point is the mean of at least four threshold measurements, with error bars representing ± 1 S.D. Fig. 2 presents the data collected from these same observers with a 6 cpd grating. All these adaptation functions are similar in shape. They were fitted with an exponential decay function of the form

$$\log C(t) = a + b \cdot e^{-kt} \tag{2}$$

where $\log C(t)$ is the contrast threshold in log units at time t; a is the fully adapted log contrast threshold; b is the initial increase in log contrast threshold due to the adapting field; and $-k$ is the decay constant. This equation was fitted to each data set by a least-squares criterion.[2]

[2] Parameter values for all data sets are available from the corresponding author.

The effect of different adapting fields on contrast thresholds at the lowest test field illuminance (−0.4 log td) can be seen by comparing the data represented by squares and solid curves in Fig. 1. For these conditions the adapting field was above the test field by 3 (black squares), 2.5 (open squares), or 2 log td (slashed squares). Higher adapting fields increased contrast threshold for all observers and slowed the course of recovery. The threshold increase and delay of recovery is especially marked for the two older observers (lower panel), who were unable to perform the task within the first 2 s after offset of the highest adapting field (2.6 log td). Similar comparisons can be made for the middle test field (0.1 log td), represented by triangles and dashed curves, and for the highest test field (0.6 log td), shown by black circles and dotted curves. The two additional observers, tested only on −0.4 log td, performed similarly.

Fig. 2 uses the same symbols and line styles as Fig. 1 to represent the data obtained with 6 cpd Gabor patches. Black squares are missing from all the individual graphs; all observers were unable to do this task within the first 10 s after a test field of −0.4 log td replaced an adapting field of 2.6 log td, 3 log units higher. Only one observer (KS) was able to perform the task at this level with a 2.1 log td adapting field (open squares), and only the two younger observers (upper panel) with a 1.6 log td adapting field (slashed squares). One of the older observers (CS) could discriminate the 6 cpd grating on a test field of 0.1 log td (triangles) only after more than 8 s had elapsed since adapting field offset. The two additional observers, tested only on the 0.1 log td test field, performed like an age-mate in the principal group.

5. Discussion

These results show that recovery of sensitivity following offset of a low photopic adapting field involves one or more processes that may take much longer than the 1000 ms typically studied in most research on light adaptation dynamics. They are in good general agreement with Bodmann et al. (1987), whose data also

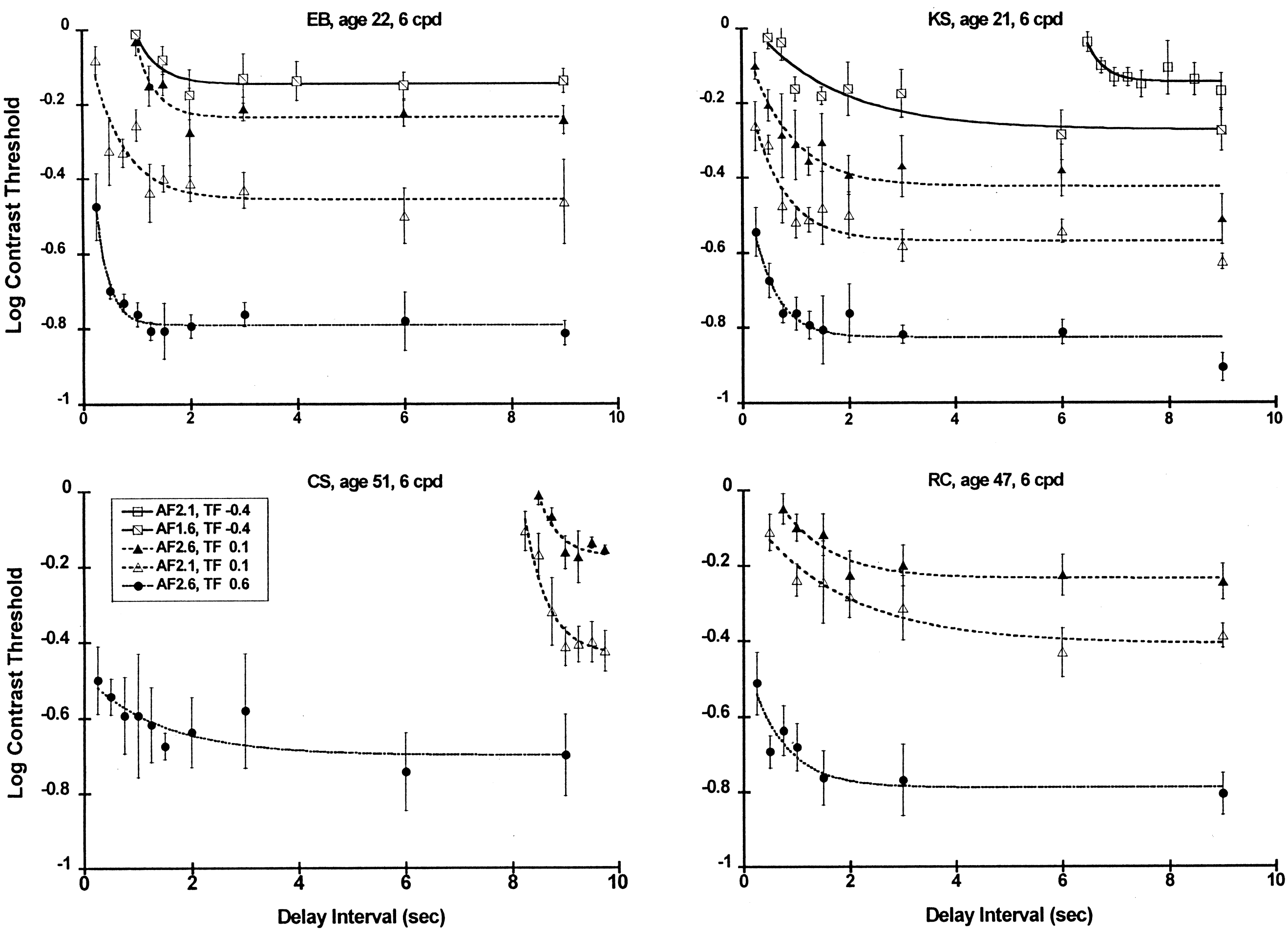

Fig. 2. Log contrast threshold plotted as a function of delay interval for 6 cpd gratings. Symbol key denotes adapting field (AF) and test field (TF) illuminances in log trolands.

followed a time course described by an exponential decay function. Our data tend therefore to support the view of Hayhoe et al. (1987) that there is a slow component to the subtractive mechanism in gain control and that this mechanism is slower at *offset* than at *onset* of an adapting background. Bodmann et al. (1987) also observed more sensitivity loss and less rapid recovery when the luminance change was downward rather than upward.

5.1. Age effects

Recovery of sensitivity after light adaptation was slower for our older than for our younger observers. This finding is not attributable to reduced retinal illuminance for older observers because effective pupillary area was held constant by use of Maxwellian-view optics and ocular media density differences are small (≤ 0.07 log unit) over our age range and stimulus wavelength. Differences between younger and older observers were not unexpected, because conventional dark adaptation studies have shown age-related declines in both cone and rod adaptation rate and in sensitivity achieved when adaptation is complete (reviewed by Werner & Schefrin, 2000).

Since the conditions of our study differ in important respects from those employed in other experiments, we have made comparisons with a few representative studies. Visual acuity data reported by Shlaer (1937) include the retinal illuminance range studied here. His data show that our lowest test field (-0.4 log td) was well above the threshold for seeing either 1 or 6 cpd under Shlaer's conditions of prolonged viewing and adaptation to the same luminance level. Log contrast thresholds reported by Patel (1966) for a 'typical' observer continuously adapted to the mean illuminance at which he was tested (0.48 log td) are also very similar to the log contrast thresholds our observers achieved within the 9 s following offset of a brighter adapting field.

Most probe-flash studies have employed a detection criterion rather than a discrimination criterion. Yang, Qi, and Makous (1995) used a 2-AFC procedure to determine contrast thresholds for detecting sinusoidal gratings (0.019–41 cd/m^2) following adaptation to a masking field of 0, 2, or 4 cpd. Since they provide information on pupil size, their data can be specified in terms of retinal illuminance for comparison with data from our observers, performing a discrimination task following adaptation to an unpatterned (0 cpd) field at higher mean illuminance. At similar illuminance levels the log amplitude sensitivity values reached by our younger observers are 0.2–0.4 log units lower than those reported by Yang et al., a reasonable difference recognizing that our experiment used what Thomas (1985) calls a classification procedure. In terms of d', given the common assumptions in Signal Detection Theory, accuracy in a classification procedure is expected to be lower by a factor of $\sqrt{2}$ than in Yang et al.'s true 2-AFC procedure.

These comparisons show that the log contrast thresholds achieved by observers in the present study are in good general agreement with visual acuity and contrast sensitivity data obtained at similar levels of retinal illuminance. They allow us to conclude that adaptation to a mean illuminance 2–3 log units higher than the test illuminance delays the recovery of spatial resolution by at least 1 s and possibly several seconds, depending on spatial frequency of the test pattern. Kortum and Geisler (1995) found a difference in detection threshold due to spatial frequency only at test fields of low mean illuminance (below 2 log td). They suggest that the explanation lies in 'spatial channels with different nonlinear response functions'. Our data confirm that there is a difference in discrimination threshold due to spatial frequency and that it is accompanied by a difference in recovery time.

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